CONSTRAINTS ON EXTRA-DIMENSIONS AND VARIABLE CONSTANTS FROM COSMOLOGICAL GAMMA-RAY BURSTS

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Abstract. The observation of the time delay between the soft emission and the high-energy radiation from cosmological gamma ray bursts can be used as an important observational test of multi-dimensional physical theories. The main source of the time delay is the variation of the electromagnetic coupling, due to dimensional reduction, which induces an energy dependence of the speed of light. For photons with energies around 1 TeV, the time delay could range from a few seconds in the case of Kaluza–Klein models to a few days for models with large extra-dimensions. Based on these results we suggest that the detection of the 18-GeV photon ∼4500 s after the keV/MeV burst in GRB 940217 provides a strong evidence for the existence of extra-dimensions. The time delay of photons, if observed by the next generation of high energy detectors, like, for example, the SWIFT and GLAST satellite based detectors, or the VERITAS ground-based TeV gamma-ray instrument, could differentiate between the different models with extra-dimensions.

Keywords: cosmology-extra-dimensions, gamma rays, bursts-radiation mechanisms, photon delay

1. Introduction

One of the most challenging issues of modern physics is the possible existence of the extra-dimensions of the space-time continuum. Multi-dimensional geometries are the natural framework for the modern string/M theories (Witten, 1996) or brane models (Horava and Witten, 1996). String models also provide a natural and self-consistent explanation for the possible variation of the fundamental constants (Forgacs and Horvath, 1979). Hence the problem of the extra-dimensions of the space-time continuum is closely related to the problem of the variations of the fundamental constants, like, for example the fine structure constant α or the speed of light c. Most of the multi-dimensional theories contain a built-in mechanism, which allows the variation of α and c. The speed of propagation of particles in vacuum is modified due to the supplementary effects induced by the extra-dimensions.

The confirmation that at least some gamma-ray bursts (GRBs) are indeed at cosmological distances raises the possibility that observations of these could provide interesting constraints on the fundamental laws of physics. The study of short-duration photon bursts, propagating over cosmological distances, is the most promising way to probe the effects related to the existence of extra-dimensions and quantum gravity effects. Data on GRBs may be used to set limits on variations in the velocity of light. This has been illustrated, by using BATSE and OSSE observations of the GRBs that have recently been identified optically, and for which precise redshifts are available, in Ellis et al. (2000).

It is the purpose of the present paper to consider the effects of the existence of the extra-dimensions on the propagation of high energy photons. Based on the expressions for the photon time delay we suggest that the detection of the 18-GeV photon ~4500 s after the keV/MeV burst in GRB 940217 provides a strong evidence for the existence of a multi-dimensional Universe.

The present paper is organized as follows. In Section 2, we review the main physical mechanisms for TeV photon emission from GRB's. The time delay of photons in multi-dimensional cosmological models is considered in Section 3. We discuss and conclude our results in Section 4.

2. TeV Photons from Gamma-Ray Bursts

The mechanisms for TeV photon production in GRBs have been reviewed recently by Wang et al. (2004). One such mechanism is the electron inverse Compton emission in GRB shocks, with an energy spectrum that can be commonly described as $\nu F_\nu \propto \nu^{-p+1/2}$, with $2.05 < p < 2.9$. On the other hand, in the reverse shocks the TeV spectrum is given by $\nu F_\nu \propto \nu^{-p/2+1}$, where $2 < p < \sqrt{6}$.

Similar to the electrons, protons can also be accelerated up to ultra-high energies higher than 10^{20} eV (Wang et al., 2004), producing a spectrum characteristic of Fermi mechanism $dN_\mathrm{p}/dE_\mathrm{p} \propto E_\mathrm{p}^{-p}$, where E_p is the energy of the proton. These protons, accelerated in both internal and external shocks can produce gamma rays with energies of the order of TeV (Wang et al., 2004). The protons can be accelerated up to 10^{20}–10^{21} eV for $\Gamma_0 = 10^2$–10^3 and therefore the energy of the synchrotron photons can extend to the TeV band for $\epsilon_\mathrm{B} n \sim 1$, where ϵ_B is the shock energy carried out by the magnetic field and n is the number density of the external medium. The energy spectrum from proton-synchrotron radiation is $\nu F_\nu \propto \nu^{(3-p)/2}$. If the spectrum of the accelerated protons is that of the standard shock theory, then $(3-p)/2 \approx 0.5$ (Wang et al., 2004).

TeV gamma rays emitted from extra-galactic sources may collide with diffuse cosmic infrared background photons, leading to secondary e^+e^- electron-positron pairs. The pair production optical depth $\tau_{\gamma\gamma}$ depends on the spectral energy distribution and the intensity of the cosmic infrared background. Because of the high redshift of the cosmological GRB sources, $\tau_{\gamma\gamma}$ also depends on the evolution of the cosmic infrared background with the redshift.

For TeV γ-photons the pair production cross section is maximized when the soft photon energy ϵ_IR is in the infrared range. For a 1 TeV gamma ray this corresponds to a soft photon wavelength near the K-band (~2 μm). Thus, infrared photons with wavelengths around 2 μm will contribute most to the absorption of TeV gamma rays. Absorption of γ-rays of energies below ~15 GeV is negligible (Stecker et al., 1992).

To estimate the number of high-energy photons from a gamma-ray burst we assume that the source gives a continuous spectrum, from keV to TeV photons. The fluence (the energy per unit area) F_γ can be represented, as a function of the photon energy E_γ, in the general form $F_\gamma(E_\gamma) = CE_\gamma^{-\beta}\exp(-\tau_\gamma)$, where we assume that β is a (model dependent) constant. The proportionality constant can be obtained from the observational result that the observed fluence, for $E_\gamma \sim 100$ keV, is of the order of $F_\gamma\left(E_\gamma = 100\text{ keV}\right) \sim 10^{-6}$–$10^{-4}$ erg cm^{-2}. Then the fluence can be represented as

$$F_\gamma(E_\gamma) = (10^{-6}\text{–}10^{-4})10^{-7\beta}\left(\frac{E_\gamma}{1\text{ TeV}}\right)^{-\beta} e^{-\tau_\gamma}\text{ erg cm}^{-2}. \tag{1}$$

The photon number N_γ, which can be observed by a detector with collection area $A_{\rm col}$, is given by

$$N_\gamma(E_\gamma) = 1.602 \times (10^{-6}\text{–}10^{-4}) \times 10^{-7\beta} \times \left(\frac{E_\gamma}{1\text{TeV}}\right)^{-\beta-1} \times e^{-\tau_\gamma} \times A_{\rm col}. \tag{2}$$

By using Eq. (2) one could estimate the number of TeV photons that could be detected by using one of the next-generation of ground based TeV gamma ray instruments, the VERITAS system. It consists of a seven, 12-m aperture telescopes, with six telescopes located at the corners of a hexagon of side 80 m (Weekes, 2004a). For TeV photons the photon collection area for this system can be as large as 5×10^8 cm^2. For the VERITAS ground-based array the variation of $A_{\rm col}$ is represented, as a function of the photon energy E_γ, in Figure 1.

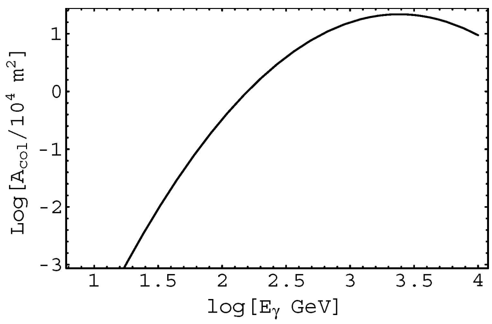

Figure 1. Variation, as a function of the photon energy E_γ, of the photon collection area $A_{\rm col}$ for the VERITAS ground-based TeV gamma-ray instrument.

The number of high energy TeV photons is represented, for three different gamma ray emission models and for two optical depth models (corresponding to the lower and upper limit of the infrared extra-galactic background, respectively), in Figures 2 and 3.

Hence, as one can see from Figures 2 and 3, the large collection area, which for the VERITAS-4 array is of the order of 2.2×10^5 m^2 for 10 TeV photons (Weekes, 2004a), makes possible the detection of high energy photons from GRBs with redshift z smaller than 0.3–0.5.

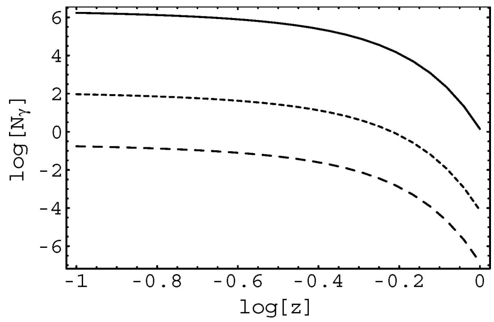

Figure 2. Variation of the photon number N_γ, for a $E_\gamma = 1$ TeV photon energy, as a function of the redshift z (in a logarithmic scale) for different high energy TeV gamma-ray production models: proton synchrotron radiation ($\beta = -0.5$) (solid curve), electron inverse Compton scattering emission in internal shocks ($\beta = 0.11$) (dotted curve) and gamma ray emission via inverse electron Compton scattering in external forward shocks ($\beta = 0.5$) (dashed curve). The optical depth for pair production is calculated by considering the lower limit for the extra-galactic infrared field density. The assumed collection area of the detector is of the order $A_{\rm col} = 5 \times 10^8$ cm^2.

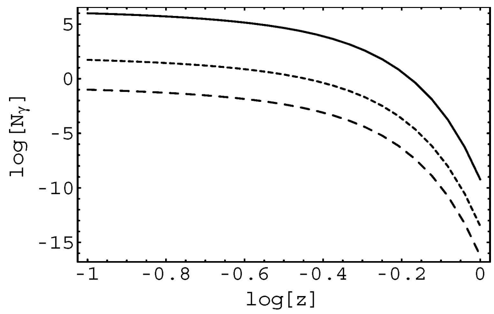

Figure 3. Variation of the photon number N_γ, for a $E_\gamma = 1$ TeV photon energy, as a function of the redshift z (in a logarithmic scale) for different high energy TeV gamma-ray production models: proton synchrotron radiation ($\beta = -0.5$) (solid curve), electron inverse Compton scattering emission in internal shocks ($\beta = 0.11$) (dotted curve) and gamma ray emission via inverse electron Compton scattering in external forward shocks ($\beta = 0.5$) (dashed curve). The optical depth for pair production is calculated by considering the upper limit for the extra-galactic infrared field density. The collection area of the detector is of the order $A_{\rm col} = 5 \times 10^8$ cm^2.

3. Photon Delay in Multi-Dimensional Universes

The energy-dependence of the speed of light of the photon due to the presence of an extra-dimension is given by Harko and Cheng (2004)

$$c = c_0\left[1 + \varepsilon\left(\frac{E}{E_K}\right)^{\beta}\right], \tag{3}$$

where we denoted $E_K = c^4 \Delta v / G$, with $\Delta v = v - v^0$ describing the variation of the size of the fifth dimension between the moments of the emission and detection of a photon. $\varepsilon = \pm 1$ is a constant, related to the sign of the fifth dimension.

In the case of isotropic homogeneous cosmological models with large non-compact extra-dimensions there is a non-zero contribution in the four-dimensional space-time (the brane) from the *five*-dimensional Weyl tensor from the bulk, expressed by a scalar term U, called dark radiation (Chen et al., 2002). The "dark radiation" term is a pure five-dimensional effect.

By taking into account the expressions for the variation of the speed of light we obtain the following general equation describing the time delay of two photons with different energies (Harko and Cheng, 2004):

$$\Delta t = H_0^{-1} f^{(\beta)}(E_1, E_2) \int_0^z \frac{(1+z)^{\beta - 1}}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3 + \Omega_U (1+z)^4}} dz, \tag{4}$$

where $H_0 = 72$ km s^{-1} Mpc^{-1}, $\Omega_M \approx 0.3$ and $\Omega_\Lambda \approx 0.7$ are the mass density parameter and the dark energy parameter, respectively. Ω_U is the dark radiation parameter and the function $f^{(\beta)}(E_1, E_2)$ describes the different physical models incorporating extra-dimensional and/or quantum gravitational effects. For $\beta = 1$ we have the linear model, with $f^{(1)}(E_1, E_2) = \Delta E / E_K^{(1)}$, where we denoted $\Delta E = E_1 - E_2$.

The linear model corresponds, from the point of view of the extra-dimensional interpretation, to an Einstein–Yang–Mills type model. A linear energy dependence of the difference of the photon velocities has also been considered in Ellis et al. (2003).

A quadratic model of the form $f^{(2)}(E_1, E_2) = (\Delta E / E_K^{(2)})^2$, can also be considered in quantum gravitational models, in which selection rules, such as rotational invariance, forbid first order terms (Ellis et al., 2003). The function $f^{(3)}(E_1, E_2) = (E_1^3 - E_2^3)/E_K^{(3)}$, corresponding to $\beta = 3$, describes the effect of a pure five-dimensional gravity on the propagation of light in four-dimensions. In the above equations we denoted by $E_K^{(\beta)}$, $\beta = 1, 2, 3$ the energy scales associated with the different types of extra-dimensional and/or quantum gravity mechanisms.

If the effects of extra-dimension do exist, then the detected time profiles between the KeV/MeV/GeV burst and the TeV burst should be very different. The comparison of the time profiles at the emitter and observer is presented in Figure 4.

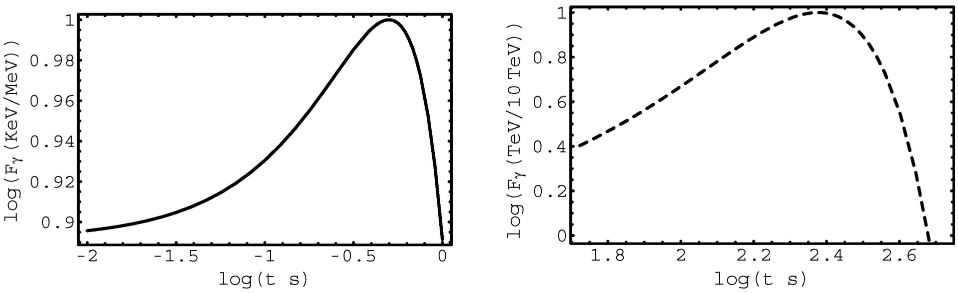

Figure 4. Comparison, in arbitrary units, of the initial KeV/MeV time profile of the GRB emission occurring at a redshift $z = 3$ (assumed to have a Gaussian form), with a duration of $\tau = 1$ s (solid curve), and the TeV time profile at the detector, modified due to the presence of multi-dimensional effects, for the linear model, with the fundamental energy scale $E_K = 1.2 \times 10^{19}$ GeV (dashed curve). For the mass and dark energy parameters we have used the values $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$, respectively.

4. Discussions and Final Remarks

By using Eq. (4) we can evaluate the extra-dimensional and/or quantum gravity energy scale, which follows from the time delay of the 18 GeV photon in GRB 940217 (Hurley et al., 1994). GRB 940217 is a very strong burst, with a total fluence above 20 keV of $(6.6 \pm 2.7) \times 10^{-4}$ erg cm^{-2} and a duration of $\sim$180 s in the BATSE range. After the low-energy emission has ended, an 18 GeV energy photon and 36 photons with 137 MeV energy have been recorded, after $\sim$5400 s following the low energy emission. Assuming that the photon originated at $z \sim 2$ and taking $\Delta t \approx 4500 \pm 800$ s, where we have also included the uncertainty in the moment of photon emission during the burst, we obtain for the linear energy scale the value $E_K^{(1)} \approx (1.75\text{–}2.51) \times 10^{15}$GeV.

This value is very close to the value $E_K^{(1)} \approx 6.9 \times 10^{15}$ GeV obtained by using a wavelet technique analysis of BATSE and OSSE data (Ellis et al., 2003). For the quadratic model energy scale we have $E_K^{(2)} \approx (1.77\text{–}2.12) \times 10^8$GeV.

In the case of quadratic quantum gravity corrections the corresponding energy scale, derived by using BATSE and OSSE data, is $E_K^{(2)} \geq 2.9 \times 10^6$ GeV (Ellis et al., 2003). For the pure Einstein gravity five-dimensional model we obtain $E_K^{(3)} \approx (8.28\text{–}9.34) \times 10^5$GeV.

From the point of view of multi-dimensional theories, the linear model could describe the effects on the propagation of light in Randall–Sundrum or Einstein–Yang–Mills type models (Harko and Cheng, 2004). The quadratic model is specific for quantum gravity effects, while the $\beta = 3$ case could describe the case of pure Einstein gravity in five dimensions. In all these cases the delay of the 18 GeV photon fixes the corresponding energy scales.

The remarkable concordance between the linear quantum gravity/extra-dimensional energy scale obtained from the present study of the time delay of the 18 GeV photon in GRB 940217 and from the independent study of the BATSE and OSSE data (Ellis et al., 2003) strongly suggest that this time delay could be the signature of the extra-dimensions or/and quantum gravitational effects.

There are several proposed, satellite-based GRB research projects. SWIFT, a multi-wavelength GRB observatory will be launched in early 2004. It has the optimum capabilities in determining the origin of GRBs and their afterglows, providing redshifts for the bursts and multi-wavelength light curves. A wide-field gamma-ray camera will detect approximately 1000 GRBs in 3 years with a sensitivity five times fainter than the BATSE detector aboard Compton GRO. Sensitive narrow-field X-ray and UV/optical telescopes will be pointed at the burst location in 20 to 70 s by an autonomously controlled "swift" spacecraft. SWIFT will acquire high-precision locations for gamma ray bursts and will rapidly relay a 1-4 arcmin position estimate to the ground within 15 s (http://swift.gsfc.nasa.gov, 2003).

Another satellite-based experiment, the Gamma-ray Large Area Space Telescope (GLAST), a high energy (30 MeV–300 GeV) gamma-ray astronomy mission, is planned for launch at the end of 2006 (Weekes, 2004a; Weekes, 2004b). GLAST should detect more than 200 GRBs per year, with sensitivity to a few tens of GeV for a few bursts. GLAST could also detect the energy- and distance-dependent dispersion of (10 ms / GeV / Gpc), predicted by quantum gravity and multi-dimensional models within 1–2 years of observations (Harko and Cheng, 2004).

The possibility that the very high energy component of the gamma-ray bursts might be delayed makes the detection with the sensitive ground-based atmospheric telescopes more feasible. The time delay between the registration of the MeV burst and its notification to the ground-based observer can be as little as 10 s. The slew times for the large telescopes varies from 20 s to 5 min., but can be much less if the observing target for the telescope happens to be close to the gamma ray source direction. In principle the telescope can continue to monitor the source position for up to 8 h (depending on its elevation and the position of Sun and Moon) and on succeeding nights.

The sensitivity that can be achieved is, for the current Whipple 10-m telescope of the order of 8×10^{-8} ergs/cm^2 for a duration of the burst of 1 and 10 s, and of 2.4×10^{-7} ergs/cm^2 for a 100 s duration burst. For the proposed VERITAS array of telescopes (Weekes, 2004a) the minimum fluence is 10^{-8} ergs/cm^2 for 1 and 10 s bursts and 3×10^{-8} ergs/cm^2 for 100 s bursts.

These data can be regarded as representative of the present generation of operating telescopes and for those that will come on-line the next few years (CANGAROO III, HESS, MAGIC and VERITAS). Delayed gamma-ray bursts will be also dispersed, since the velocity of light is a function of energy; hence the energy resolution of the detectors will be critical. The minimum detectable fluence is limited by the duration of the burst. For short times the fluence is limited by the number of photons, since there is virtually no background (Weekes, 2004b).

Therefore, the detection of the time delay between Tev and GeV/MeV photons from GRBs could represent a new possibility for the study and understanding of some fundamental aspects of the physical laws governing our universe.

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